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FINAL TECHNICAL REPORT

1. Title: A Study of Gravity Wave Variability, Saturation, and Turbulence Generation in the Mesosphere and Lower Thermosphere

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2. Research Summary

This report summarizes research performed under three years of ONR support. Our principal research objectives were to understand the characteristics of and the processes controlling the fluctuations of velocity, density, and optical properties due to wave and turbulence motions in the middle atmosphere. It was hoped that an increased understanding of these motions and their variability would lead to a better predictive capability for their influence on in situ and ground-based systems ~~utilizing~~ this region in the future. The sponsored research has made considerable advances in addressing these goals and provided a much enhanced understanding of middle atmosphere motions and their environmental influences.

Research progress was made on several fronts. Theoretical efforts focussed on wave propagation and saturation processes, the effects of varying stratification on wave saturation and wave transports of energy and momentum, and the influences of chemical recombination on ion and neutral fluctuations due to waves and turbulence. Observational studies using in situ data collected with instrumented sounding rockets addressed the small-scale structure of turbulence and its association with the large-scale wave field. Horizontal variations of density were studied using data obtained during space shuttle re-entries. Finally, radar data were used to examine the character and implications of the vertical velocity field over northern Norway, horizontal and vertical velocity variances and momentum fluxes at Poker Flat, Alaska, and the

characteristics and variability of radar backscatter using multiple frequencies during the MAC/SINE experiment.

Three studies (Fritts and Yuan, 1989a; Fritts and Yuan, 1989b; Yuan and Fritts, 1989) examined the propagation and ducting of gravity waves in a variable environment and the nature of instability of inertio-gravity wave motions. The first study suggested that environments with variable velocity and stability profiles provide numerous locations at which relatively high-frequency wave motions can be ducted, that such ducts are easily coupled due to complex modal structures, and that such an environment may enhance the vertical coupling and transports of energy and momentum by waves with high intrinsic frequencies. The stability studies provided further evidence that inertio-gravity waves (with $\omega \sim f$) are preferentially unstable only to dynamical (Kelvin-Helmholtz type) instabilities, suggesting a clear distinction in the nature of instability of low- and high-frequency wave motions and their influences on wave and spectral amplitudes.

A model of the saturated vertical wavenumber spectrum was employed by VanZandt and Fritts (1989) to examine the effects of varying stratification on wave saturation and energy and momentum transports. The implications of larger forcing of the mean flow and larger levels of turbulence and diffusion in regions of increased stratification near the tropopause and summer mesopause appear to be in qualitative agreement with observations near the mesopause and the needs of large-scale models in both regions. If this theory proves to be a fair description of the influences of wave saturation, then it could have important applications in the predictions of wave forcing and in the development of a new generation of gravity wave parameterization in large-scale dynamical/chemical/radiative models of the atmosphere.

The theoretical study by Fritts and Thrane (1990) of the relationship between ion and neutral density fluctuations has revealed that the phase of the ion/neutral density ratio is a function of the intrinsic frequency of the motion causing the fluctuations. This phase may change by 180°, depending on whether motions are adiabatic and high-frequency or slow and dominated by chemical effects. These results have important implications for the use of ion or electron density measurements for wave and turbulence studies.

In situ studies of wave-turbulence interactions were performed by Goldberg et al. (1988) and Blix et al. (1990). The former revealed variations in radar backscatter

in regions of enhanced particle precipitation that correlated well with wave structure at small vertical scales (a few km), suggesting high-frequency motions as an important contributor to the vertical flux of wave energy. The study by Blix et al. (1990) used data from several in situ instruments to examine the intensity and structure of turbulence and its correlation with the large-scale wave field. Ion probe data provided resolution of scales extending from the viscous range ($\sim k^{-7}$) through the inertial range ($\sim k^{-5/3}$) and into a range at large scales coinciding with either gravity waves or buoyancy range turbulence ($\sim k^{-3}$). Ion density variance within the inertial range was used to infer turbulence intensities and revealed a good correlation with the sites of expected instability within the wave field. Together with the theoretical stability studies discussed above, these observational results provide evidence of the general validity of the wave saturation theory.

Data obtained during seven space shuttle re-entries were used by Fritts et al. (1989) to infer neutral density fluctuations along approximately horizontal trajectories between 60 and 90 km altitudes over the central Pacific. These were used to assess the potential energy in the wave field and the horizontal wavenumber composition of the wave spectrum. Wave amplitudes were inferred to be substantially smaller than over major land masses, but the growth of wave energy with height was found to be consistent with observations using other techniques. A significant finding in this work was the large variance associated with motions at small horizontal scales (~ 10 - 100 km), suggesting that such motions may account for a majority of the upward fluxes of wave energy and momentum.

Finally, radar data obtained using several different facilities were used to examine various aspects of the motion field and scattering properties near the summer mesopause. A study by Fritts et al. (1990) examined the vertical velocity field during the MAC/SINE experiment and found a dynamically active environment with large variances, a downward Eulerian mean velocity (suggesting an upward flux of wave energy to account for a true upward mean motion), frequency spectra suggestive of highly variable Doppler shifting environments, and vertical wavenumber spectra in general agreement with the expectations of saturation theory. A study using data from Poker Flat, Alaska by Fritts and Yuan (1989c) examined the means, variances, momentum fluxes, and variability of the velocity field near the mesopause and provided evidence of wave forcing of the mean flow substantially stronger than observed at lower latitudes. This strong forcing plays an important role in determining the large-scale circulation and the thermal and constituent structures

of this region of the atmosphere. Finally, a study by Hoppe et al. (1990) used radar data collected at several frequencies to examine the nature and variability of radar backscatter near the summer mesopause. An important finding here was the observation of an inverse relation between backscatter signal and spectral width, suggesting a non-turbulent process responsible for the echoes that may be due to scavenging of free electrons by summer mesopause cloud particles or the influence of heavy ion clusters.

3. Research Publications

Listed below are all the publications acknowledging support by the Office of Naval Research under this contract.

Fritts, D.C., 1987: Recent progress in gravity wave saturation studies, Transport Processes in the Middle Atmosphere, NATO Advanced Studies Workshop, G. Visconti and R. Garcia, Eds., 31-46.

Goldberg, R.A., D.C. Fritts, H.-G. Chou, J.R. Barcus, and F.J. Schmidlin, 1988: Studies of high latitude mesospheric turbulence by radar and rocket. 1: Energy deposition and wave structure, J. Atmos. Terres. Phys., 50, 951-968.

Fritts, D.C., 1989: A review of gravity wave saturation processes, effects, and variability in the middle atmosphere, Pure Appl. Geophys., 130, 343-371.

Fritts, D.C., 1989: Gravity wave saturation, turbulence, and diffusion in the atmosphere: Observations, theory, and implications, Parameterization of Small-Scale Processes, 'Aha Huliko'a workshop proceedings, P. Muller and D. Henderson, Eds., 219-234.

Fritts, D.C., R.C. Blanchard, and L. Coy, 1989: Gravity wave structure between 60 and 90 km inferred from space shuttle re-entry data, J. Atmos. Sci., 46, 423-434.

Fritts, D.C., and L. Yuan, 1989a: An analysis of gravity wave ducting in the atmosphere: Eckart's resonances in Thermal and Doppler ducts, J. Geophys. Res., 94, 18455-18466.

Fritts, D.C., and L. Yuan, 1989b: A stability analysis of inertio-gravity wave structure in the middle atmosphere, J. Atmos. Sci., 46, 1738-1745.

Fritts, D.C., and L. Yuan, 1989c: Measurement of momentum fluxes near the summer mesopause at Poker Flat, Alaska, J. Atmos. Sci., 46, 2569-2579.

VanZandt, T.E., and D.C. Fritts, 1989: A theory of enhanced saturation of the gravity wave spectrum due to increases in atmospheric stability, Pure Appl. Geophys., 130, 399-420.

Yuan, L., and D.C. Fritts, 1989: Influence of a mean shear on the dynamical instability of an inertio-gravity wave, J. Atmos. Sci., J. Atmos. Sci., 46, 2562-2568.

Blix, T.A., E.V. Thrane, U.-P. Hoppe, D.C. Fritts, U. von Zahn, F.-J. Luebken, W. Hillert, S.P. Blood, J.D. Mitchell, H.-U. Widdel, G.A. Kokin, and S.V.Pakhomov, 1990: Small-scale structure observed in situ during MAC/EPSILON, J. Atmos. Terres. Phys., in press.

Fritts, D.C., U.-P. Hoppe, and B. Inhester, 1990: A study of the vertical motion field near the high-latitude summer mesopause during MAC/SINE, submitted to J. Atmos. Terres. Phys.

Fritts, D.C., and E.V. Thrane, 1990: Computation of the ion/neutral density ratio in the presence of wave and chemical effects, to be J. Atmos. Terres. Phys., in press.

Hoppe, U.-P., D.C. Fritts, I.M. Reid, C.M. Hall, and T.L. Hansen, 1990: Multiple-frequency studies of the high-latitude summer mesosphere: Implications for scattering processes, submitted to J. Atmos. Terres. Phys.